SCIENCE

FRIDAY, SEPTEMBER 27, 1918

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MAGNETIZATION BY ROTATION[1]

So far as we know at present, a magnetic substance, that is a substance whose molecules are elementary magnets, can be magnetized in two ways, and only two ways: In the first place it can be be magnetized by creating a magnetic field in it or putting it in a magnetic field, as has been known for very many years; and, in the second place, it can be magnetized by simply setting it into rotation in a region initially neutral magnetically, and both initially and finally neutral electrically. It is chiefly with this latter process that we are concerned at this time.

In this process, as we shall see, the magnetization is produced *directly* by a sort of molecular gyroscopic action, which distinguishes it sharply from other processes in which *magnetic fields* are produced by rotation, but in which *magnetization* may or may not result, according to circumstances. It will be conducive to clearness to consider briefly some of these processes.

Thus if we take a tube of brass, or other non-magnetic substance, electrify it, and rotate it about its axis, a magnetic field will be produced similar in a general way to the field which would be produced by winding the tube with a coil of insulated wire and passing an electric current through it, as Rowland proved over forty years ago. So far, there is no magnetization. But if a rod of iron is introduced into the tube, and either maintained at rest or rotated with it, the rod will become magnetized—not because of its rotation, but be-

[1] An address delivered before the National Academy of Sciences, April 22, 1918. Most of the material presented here is taken from papers previously published in SCIENCE, the *Physical Review* and the *Proceedings of the National Academy of Sciences.* Detailed accounts of most of the work are given in the *Physical Review,* 6, 239, 1915, and 10, 7, 1917.

cause of the magnetic field, in this case produced by the rotation of the charges. There would be a similar result, and a similar interpretation, if the rod alone were to be given the charge and rotated.

Again, if we take a metal rod and rotate it in a magnetic field, electric currents will in general be induced in it; and the magnetic field due to these currents will, if the rod is made of magnetic material, change its magnetization. Experiments of this kind were made about one hundred years ago by Barlow, Christie and Arago.

In each of these cases, and in others which might be mentioned, a *magnetic field* is produced by the rotation, and it is this field which produces the magnetization if a magnetic substance is present.

Coming now to the other or gyroscopic process of magnetization, and starting with a neutral rod of iron or other magnetic substance, we can magnetize it directly by mere rotation, and a magnetic field will result from this magnetization.

In order to understand this process it is necessary to consider first, a simple case of the behavior of a gyroscope; and second, the modern interpretation of Ampère's theory of molecular currents.

Here we have a gyroscope whose wheel, pivoted in a light frame, can be rotated rapidly about its axis A. Except for the action of two springs, this frame and the axis A are free to move in altitude about a horizontal axis B, perpendicular to A; and the axis B and the whole instrument can be rotated about a vertical axis C. If the wheel is spun about the axis A, and the instrument then rotated about the vertical C, the wheel tips up or down so as to make the direction of its rotation coincide more nearly with the direction of the impressed rotation about the vertical axis C. If it were not for the springs the wheel would tip until the axes A and C became coincident. The greater the rotary speed about the vertical the greater is the tip of the wheel. When the wheel's speed about the axis A is zero, no tip occurs.

Now according to the modern version of Ampère's hypothesis, each molecule of a magnetic substance has a magnetic moment, or is a magnet, because it consists in part at least of electrons revolving in fixed orbits with constant angular velocities about an oppositely charged nucleus, and producing a minute magnetic field somewhat like that due to a small loop of wire traversed by an electric current.

If these electrons, revolving in the same general direction, have mass, each molecule has therefore angular momentum like the wheel of a gyroscope; and if the body of which it is a part is set into rotation about any axis, the molecule must change its orientation in such a way as to make the direction of revolution of its electrons coincide more nearly with the direction of the impressed rotation.

Only a slight change of orientation can occur on account of the forces due to adjacent molecules, which perform the function of the springs in the experiment with the gyroscope. The rotation thus causes each molecule to contribute a minute angular momentum, and thus also a minute magnetic moment, parallel to the axis of rotation; and thus the body, whose molecular magnets originally pointed in all directions equally, becomes magnetized.

If the revolving electrons are all positive, the body will become magnetized in the direction in which it would be magnetized by an electric current flowing around it in the direction of the angular velocity imparted to it. If they are all negative, or if the effect of the negative electrons is preponderant, it will be magnetized in the opposite direction. This is what actually happens.

For a simple type of molecular magnet a somewhat exact theory of the effect can be developed.

Assume the molecule (Fig. 1) to consist of n (one or more) similar electrons, all positive or all negative, with total charge ne and total mass nm, revolving in a circular orbit of radius r with constant angular velocity ω (and areal velocity $a = \frac{1}{2}\omega r^2$) about a much more massive, and fixed, nucleus with charge $-ne$.

This molecule will have a magnetic moment $\mu = nea$, a moment of inertia about the axis of revolution $C = nmr^2$, and an angular momen-

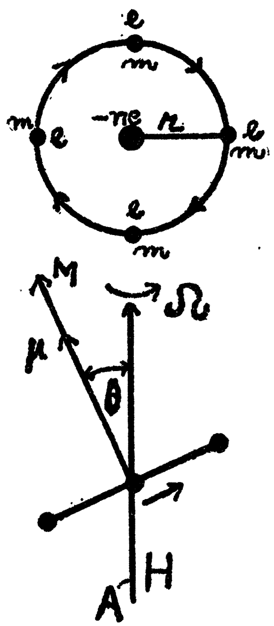

FIG. 1.

tum $M = C\omega = nmr^2\omega = 2nma$ about this same axis. The ratio of the angular momentum to the magnetic moment is

$$\frac{C\omega}{\mu} = 2\frac{m}{e}$$

The vectors representing the angular momentum and the magnetic moment are thus in the same or opposite directions according as e is positive or negative.

If now the body of which this molecule is a part is set into rotation with angular velocity Ω about an axis A, the molecule, or the orbital ring, behaving like the wheel of a gyroscope, will strive, as it were, to take up a position with its axis of revolution coincident with that of the impressed rotation; but it will be prevented from turning so far by a torque T due to the action of the rest of the body and brought into existence by the displacement. In a minute time kinetic equilibrium will be reached, and the axis of the orbit will then continuously trace out a cone making a constant angle θ with a line through its center parallel to the axis of the impressed rotation. When this state has been reached, as is known from dynamics, and as can easily be established by applying the second law of motion,[2] by Lagrange's equations, or otherwise,

$$T = \sin\theta \cdot C\omega \cdot \Omega\left(1 + \frac{1}{2}\frac{\Omega}{\omega}\cos\theta\right)$$

Now imagine the body, instead of being rotated, to be placed in a uniform magnetic field whose intensity H is directed along the previous axis of rotation, and consider a molecule whose magnetic axis, after displacement by the field, makes the angle θ with H. The

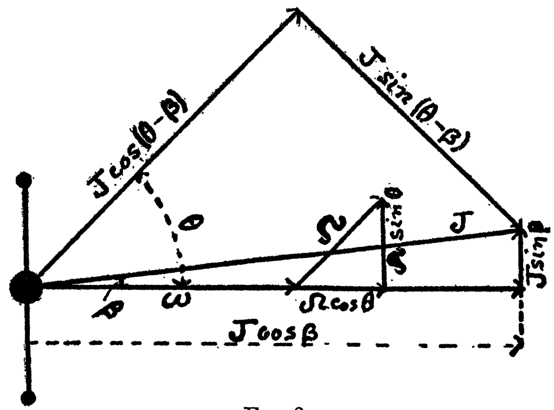

FIG. 2.

molecule would keep on turning under the action of the field until its axis coincided with H, but is prevented from doing so by the torque T' upon it due to the action of the rest of the body and brought into existence by the displacement. This torque is well known to be

$$T' = \mu H \sin\theta$$

[2] The expression for T can be found readily from Fig. 2. Let A denote the moment of inertia of the ring about a diameter, and β the angle between the vector representing J, the total angular momentum of the ring, and the vector representing ω. J can be resolved into two rectangular components, one parallel to the axis of the impressed rotation, viz., $J\cos(\theta - \beta)$, which is constant, and one perpendicular to this axis, viz., $J\sin(\theta - \beta)$, which has the constant rate of change $\Omega J \sin(\theta - \beta)$. By the second law of motion this is equal to the torque T. Expanding this expression for T, substituting for $J\cos\beta$ and $J\sin\beta$, the components of J parallel and perpendicular to the axis of the ring, their equals $C(\omega + \Omega\cos\theta)$ and $A\Omega\sin\theta$, and noting that $A = \frac{1}{2}C$, we obtain the relation sought.

To find, therefore, the magnetic intensity which would produce the same effect on the orientation of the molecule as would be produced by rotating the body at the angular velocity Ω, all we have to do is to equate T and T'. This gives

$$\mu H \sin\theta = \sin\theta \cdot C\omega\Omega\left(1 + \frac{1}{2}\frac{\Omega}{\omega}\cos\theta\right)$$

or

$$H = \frac{C\omega}{\mu}\cdot\Omega\left(1 + \frac{1}{2}\frac{\Omega}{\omega}\cos\theta\right) = 2\frac{m}{e}\Omega\left(1 + \frac{1}{2}\frac{\Omega}{\omega}\cos\theta\right)$$

The values of Ω experimentally attainable are so small in comparison with any possible values of ω that the last term is negligible. Hence we have for any molecule in the body, whatever its orientation and whether it contains one or more orbits,

$$H = 2\frac{m}{e}\Omega$$

or

$$H = 4\pi\frac{m}{e}N$$

if N denotes the angular velocity in revolutions per second.

If therefore only one kind of electricity, with fixed ratio of mass to charge, is in orbital revolution in the molecules of a magnetic body, rotating it with the angular velocity N revolutions per second is equivalent to putting it in a magnetic field of strength H, the intrinsic magnetic intensity of rotation, such that, with great precision,

$$H/N = 4\pi\frac{m}{e}$$

If we assume that negative electrons alone are in orbital revolution, the value of the second member of this equation, according to well known experiments on electrons in slow motion, is -7.1×10^{-7} electromagnetic units, and H/N should be equal to this quantity and identical for all magnetic substances. If positive electrons also participate the magnitude of H/N should be smaller.

If the Ampèreian currents consist in the motion of actual matter, so that the molecules of magnetic substances have angular momentum, an ordinary magnet or electromagnet itself should behave to some extent like a gyroscope when set into rotation. The first to see this, as well as the first to see any relation between magnetism and angular momentum, appears to have been Maxwell, who constructed apparatus for experiments on the subject as early as 1861.

In Maxwell's apparatus an electromagnet was pivoted in a circular frame in such a way as to be free to rotate about a horizontal line through its center of mass and perpendicular to its magnetic axis. With the magnetic axis making an angle θ with the vertical, the frame was rotated at high speed about a vertical axis, also passing through the magnet's center of mass, and observations were made for a change in θ, stability having been secured by suitable adjustments of the principal moments of inertia. No change could be detected, but only rough observations were possible.

In the experiments on magnetization by rotation Maxwell's electromagnet is replaced by each one of the countless multitude of molecular magnets of which the magnetic body is constituted, and the total change in the orientations of all these magnets with reference to the axis of rotation of the body is determined magnetically.[3]

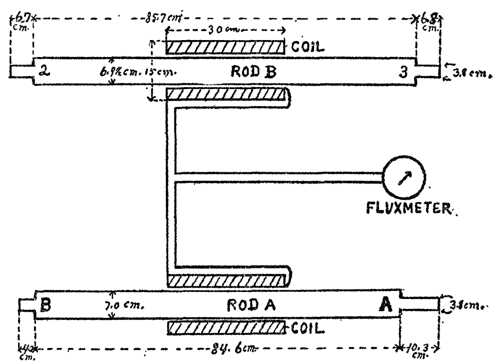

Fig. 3.

Two series of experiments have been made, both with Mrs. Barnett's assistance, and by methods as different from one another as possible. The first series of experiments was made

[3] I have learned very recently from a footnote in John Perry's *Spinning Tops* that he made experiments on this subject, with the same idea in mind, but without success, many years ago.

on large iron rods by a method depending on the principles of electromagnetic induction; the second, on smaller rods of iron, cobalt and nickel, by the method of the magnetometer. Recently a few preliminary experiments have been made on Heusler alloy.

Some of the essential parts of the apparatus used in the first investigation are shown in the diagram of Fig. 3.

Two nearly similar rods of steel shafting A and B were mounted with their axes horizontal and perpendicular to the magnetic meridian, and two similar coils of insulated copper wire were mounted about their centers. These coils were connected in series with one another and with a Grassot fluxmeter, which was the principal measuring instrument, and were oppositely wound so that that any variations in the intensity of the earth's magnetic field acting in the same way on both rods might produce

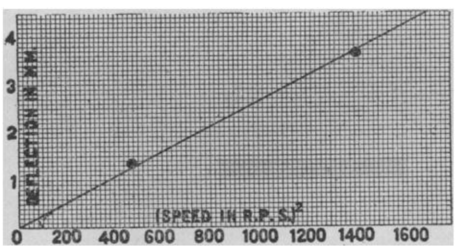

FIG. 4.

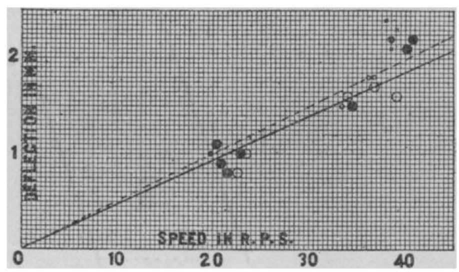

FIG. 5.

no effect on the fluxmeter. One of the rods, which will be called the compensator, as A, remained at rest; while the other, called the rotor, as B, was alternately rotated and brought to rest, the change of flux being determined by the fluxmeter, which, together with the other apparatus, was standardized by proper subsidiary experiments. For use in these experiments the rods A and B were uniformly wound with solenoids of insulated wire.

To prevent possible disturbances arising from the presence of the earth's magnetic field, the rotor was surrounded by a large electric coil which approximately neutralized the earth's intensity in the region occupied by the rotor.

The rotor was directly driven in either direction at will by an alternating current motor in part of the work, and by an air turbine in the rest.

In making observations fluxmeter deflections were obtained for each of several speeds, first with the rotation in one direction and then with the rotation in the other direction.

After making a great variety of tests, and after taking many precautions to eliminate sources of error, two effects stood out very clearly as the result of the observations, instead of the one which was looked for.

If the *mean* of the two deflections for the same speed is plotted against the square of the speed, the resulting graph is a straight line as shown in Fig. 4. The *mean* deflection is thus proportional to the square of the speed. This deflection is due to the increase of the residual magnetic flux through the rotor produced by its centrifugal expansion during rotation—an effect which was not foreseen, and which was very puzzling until its explanation became apparent. This effect would vanish if the rod were completely demagnetized initially.

If, however, the *difference* between the two deflections for the two directions of rotation, instead of the mean deflection, is plotted against the *speed,* and not against the square of the speed, a straight line again results, as shown in Fig. 5. This is the effect which was under investigation. The straight line shows that H is proportional to N, as predicted.

The earlier experiments by this method gave for H/N the mean value -3.6×10^{-7} e.m.u.; the later and more precise experiments gave -3.1×10^{-7} e.m.u., with an experimental error for a set of four double deflections equal to about 12 per cent. The graph of Fig. 5 is drawn for these observations, the dotted

straight line corresponding to the weighted mean value of the double deflection divided by the speed.

Not long after the first conclusive experiments on magnetization by rotation were presented to the American Physical Society, Einstein of Switzerland and de Haas of Holland described successful experiments on the converse effect, viz., the production of rotation by magnetization, which had been predicted and looked for by O. W. Richardson in 1907, and they have since published additional experiments. Very recently another investigation of this converse effect has been made by J. Q. Stewart. All these investigations are indirect but excellent confirmations of the work described here.

In the second investigation, as already stated, the method of the magnetometer was used. A diagram of important parts of the apparatus is given in Fig. 6.

The rod under test, or rotor, *F*, was mounted with its axis horizontal and normal to the magnetic meridian, as in the first investigation, and in the second, or equatorial, position of Gauss, which offered great advantages over the first, or polar, position for this work.

The magnetometer system, which was astatic, is shown suspended from the torsion head *A* by a silk fiber. To reduce disturbances due to variations of the earth's intensity as much as possible, a compensating rod *B* of the same substance and nearly the same size as the rotor, was mounted in approximately the same position with respect to the upper magnetometer magnet as that occupied by the rotor with respect to the lower magnet.

Possible errors due to induced currents in the rotor and to minute shifts of the rotor's axis in altitude or azimuth were avoided by compensating accurately the earth's intensity with the large electric coil *E*, as in the earlier investigation. *C* is a small electric coil in series with *E* to make the zero and sensibility approximately independent of the compensating current in the coil *E*.

The rotors were driven by an alternating current motor, operating at the same speed in both directions. Three different speeds of the rotor could be obtained by using cone pulleys.

The principal magnetometer observations consisted in getting the double deflections produced by reversing the direction of the rotation, the speed for the two directions being the same. From these readings, the speed, and the calibration experiments, *H*, could be found as a

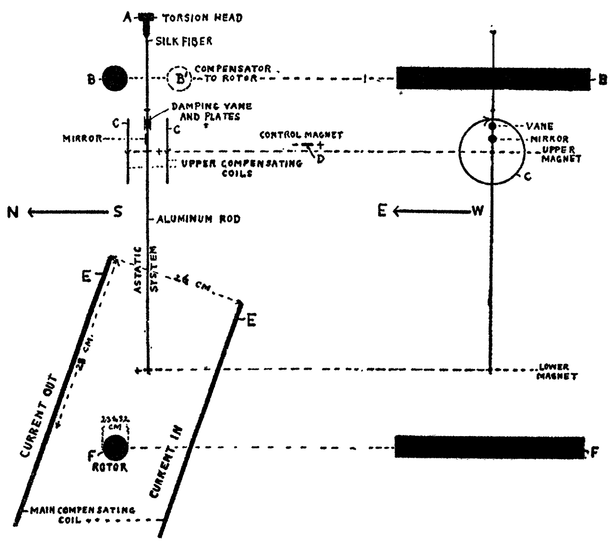

Fig. 6.

function of N. Numerous precautions were necessary as in the earlier investigation.

The results of the observations on four rotors are given in Table I. The "set" of observations there referred to contained four readings, or two double deflections.

With nickel and cobalt observations were made at more than one speed; and H/N was found to be independent of the speed, within the limits of the experimental error, as in the earlier experiments with iron. It is also seen to be independent of the size and shape of the body in rotation, which is an implicit requirement of the theory developed above.

TABLE I

Intrinsic Magnetic Intensity of Rotation in Iron, Nickel and Cobalt

Rotor	Series	Groups	Mean Speed R.P.S.	Number of Sets	$-\frac{H}{N} \times 10^7$ E.M.U. Mean	Average Departure from Mean (Sets)
Steel (smaller)	1	1–2	44.8	21	5.1	0.5
Steel (larger)	2	3–4	47.8	21	5.2	1.2
Cobalt...	3	5–7	20.2	17	4.8	2.2
	4	8–11	30.3	23	5.6	1.2
	5	12–25	45.5	79	6.0	0.9
	6	22	45.0	7	6.5	0.3
	7	24	44.8	9	5.9	0.4
	8	25	44.8	5	6.1	0.4
Nickel...	9	26	20.5	4	4.7	2.0
	10	27–28	30.5	9	6.7	1.1
	11	29–32	45.3	37	6.1	0.5

The value of H/N is in all cases negative, but less in magnitude than that of the standard value of $4\pi m/e = -7.1$ e.m.u. for negative electrons in slow motion, as was the case in the earlier experiments with iron, which gave 3.6 and 3.1 in place of 7.1. In view of the experimental errors, it still seems to me doubtful whether these discrepancies indicate definitely that in addition to the negative electrons in orbital revolution there are also positive electrons revolving in orbits. The probability of the presence of the latter orbits is great from the known expulsion of α particles with great velocities from radio-active substances. There can be no question, however, that the effect of the negative electrons is at least greatly preponderant.

A few preliminary results, not of a precise character, but consistent with those of Table I., have been obtained with a rotor of very soft iron and with a rotor of Heusler alloy—a magnetic compound of aluminum, copper and manganese in atomic proportions.

In summing up the chief results of the two investigations it may be said that, in addition to revealing a second and entirely new method of producing magnetization in magnetic substances, they have proved in a direct and conclusive way, on the basis of classical dynamics alone and without dependence on the still obscure theory of radiation, (1) that Ampèreian currents, or molecular currents of electricity in orbital revolution, exist in iron, nickel, cobalt and Heusler alloy; (2) that all or most of the electricity in orbital revolution is negative, or at least that the effect of the negative electricity is preponderant; and (3) that this electricity has mass or inertia. Furthermore, if we admit the classical theory of radiation, according to which a ring of electrons moving in a circular orbit must continually emit energy, but at a smaller rate the more uniformly the electricity is distributed in the ring, we must conclude that the electrons are closely packed in the Ampèreian orbits. For the existence of residual or permanent magnetization proves that these orbits are essentially permanent and can not therefore emit energy at an appreciable rate.

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THE ORIGIN OF THE PINK BOLLWORM

THE determination of the original habitat of the pink bollworm (*Pectinophora gossypiella* Saunders) is of great interest in relation to the present distribution of this insect and may be of importance later as indicating where parasitic or other natural checks may be found. A scrutiny of the records gives strong support to the theory that this insect originated in Southern Asia, probably India.

The first account of the insect by W. W.